Geochemical and Environmental Tracer Study of Dry Brook Hill Aquifer, South Hadley, MA

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1. Executive Summary

The goal of this study was to refine the contributing area and connections between aquifers and source waters of the Dry Brook aquifer. The results allow for improved decision-making regarding the sustainability and vulnerability of the Fire District 2 drinking water supply for the town of South Hadley. We collected a total of 63 samples from groundwater wells, Connecticut River water, streams, and a 12-hour pumping test of the Dry Brook supply well. We analyzed these waters for a suite of hydrogeochemical tracers to better understand the aquifers, surface water bodies, and connections between them in space and time. Tracers include stable Oxygen and Hydrogen isotopes in water (^{18}O, ^{2}H), Tritium in water (^{3}H), dissolved noble gases, Radon gas in water, anthropogenically produced short-term age tracers Chlorofluorocarbons (CFCs), and Sulfur Hexafluoride (SF6) and the concentration of dissolved ions. Results indicate that during the short pumping test, the aquifer water is quite stable yet slightly different geochemically and in isotopic signature than surrounding groundwaters and surface waters. Sampling done over the course of the year indicates small variability in isotopic signature that indicates an aquifer with some connection to surface water and recent precipitation, but also that the dominant water volume source is from longer flow paths and groundwater storage within the aquifer. We estimate that based on the results of this study, between 10% and 42% of the water pumped from the supply well is ultimately sourced from Connecticut River water. It's important to keep in mind though that we provide a range because of the inherent uncertainty in the results due to limitations in the sample locations, study time frame, and pump test duration. In addition, though we indicate a portion of water is likely sourced from the Connecticut River, this water is being infiltrated through 50-100 vertical feet of sediment, a process likely occurring over the course of months to decades. Our results reached through a purely hydrogeochemical tracer analysis, support the overall findings of the physical hydrological assessment described in the USGS Study of the Dry Brook Public-Supply Well.

2. Introduction

2.1. Background

A USGS study of the dry brook aquifer system developed a hydrogeologic conceptual model of the aquifer system (Garabedian and Stone, 2004). Physical hydrologic data suggest that groundwater flows from the recharge area towards the Connecticut River with a strong hydraulic connection between observation wells and the river itself. A physical hydrogeologic model that solves the groundwater flow equation determined the steady-state contributing area of the aquifer at two sustained pumping rates. The lower sustained rate of 300 GPM produced 90% of the water from local recharge vs. 10% from the Connecticut River, while the 914 GPM pumping rate produced 50% from both sources. In addition, results of a sensitivity analysis of the extent of areas contributing water to the Dry Brook well when pumped at 914 GPM indicated that the size of these areas did not substantially change when aquifer properties were varied. In contrast, however, the size of these areas changed most when the recharge rate was modified. Refining the contributing area of the aquifer and the relative sources of water is critical for making informed decisions regarding the sustainability and vulnerability of the sole-source drinking water supply for the town of South Hadley.

2.1.1. Geologic Setting

The study area lies above two different bedrock units defined by the USGS as Mesozoic Basin Sediment and Basalt. More specifically these relate to the Connecticut Valley Mesozoic Basin which comprises upper Triassic formations of Sandstone, shale, and conglomerate material interlaced by basaltic lavas and diabasic materials. The surficial geology of the area is dominated by coarse and fine glacially stratified deposits, floodplain alluvium, and alluvial-fan deposits.

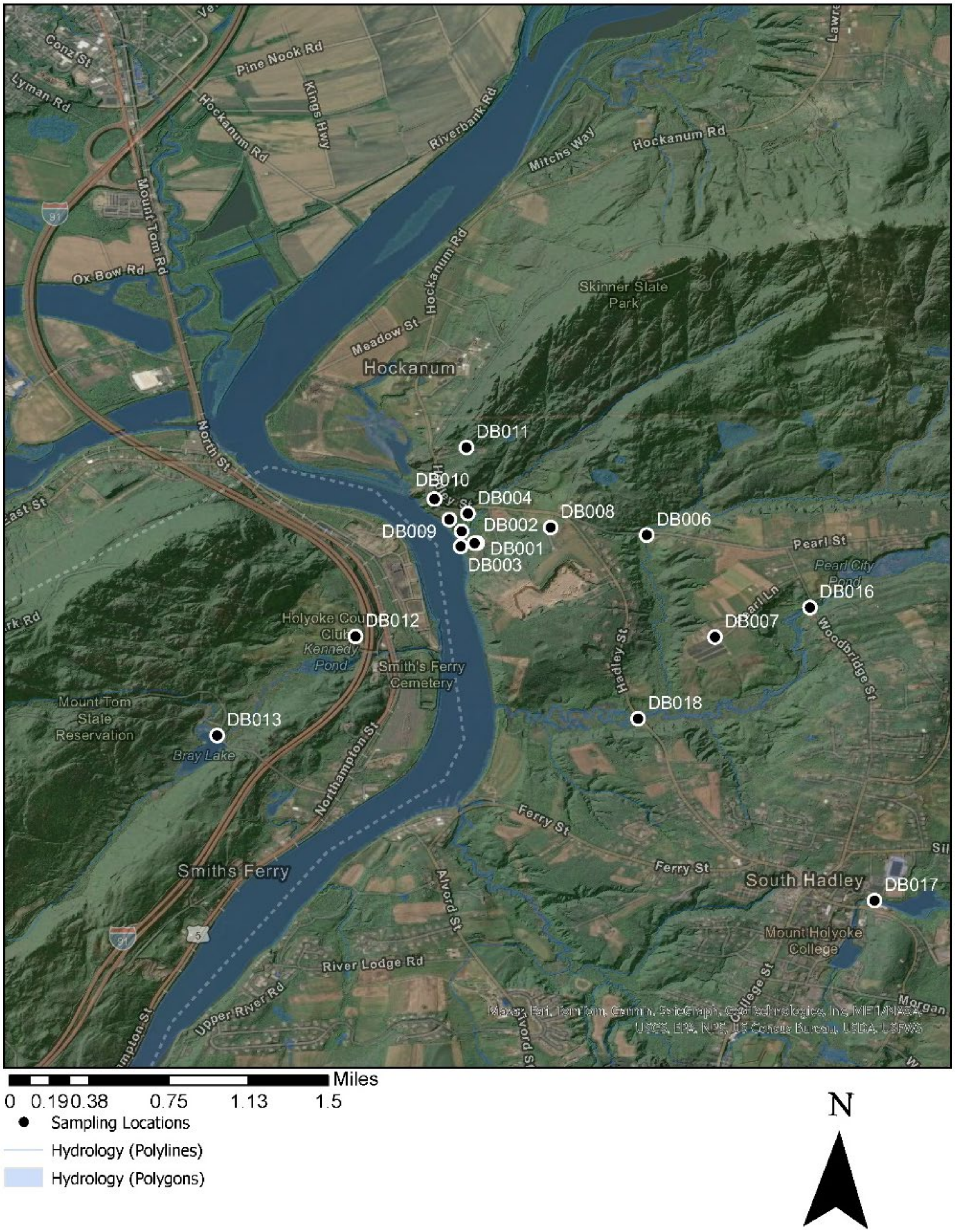


Figure 1. Map of the project site along the Connecticut River. Major wetlands, lakes, streams, and the sample locations in the study are indicated.

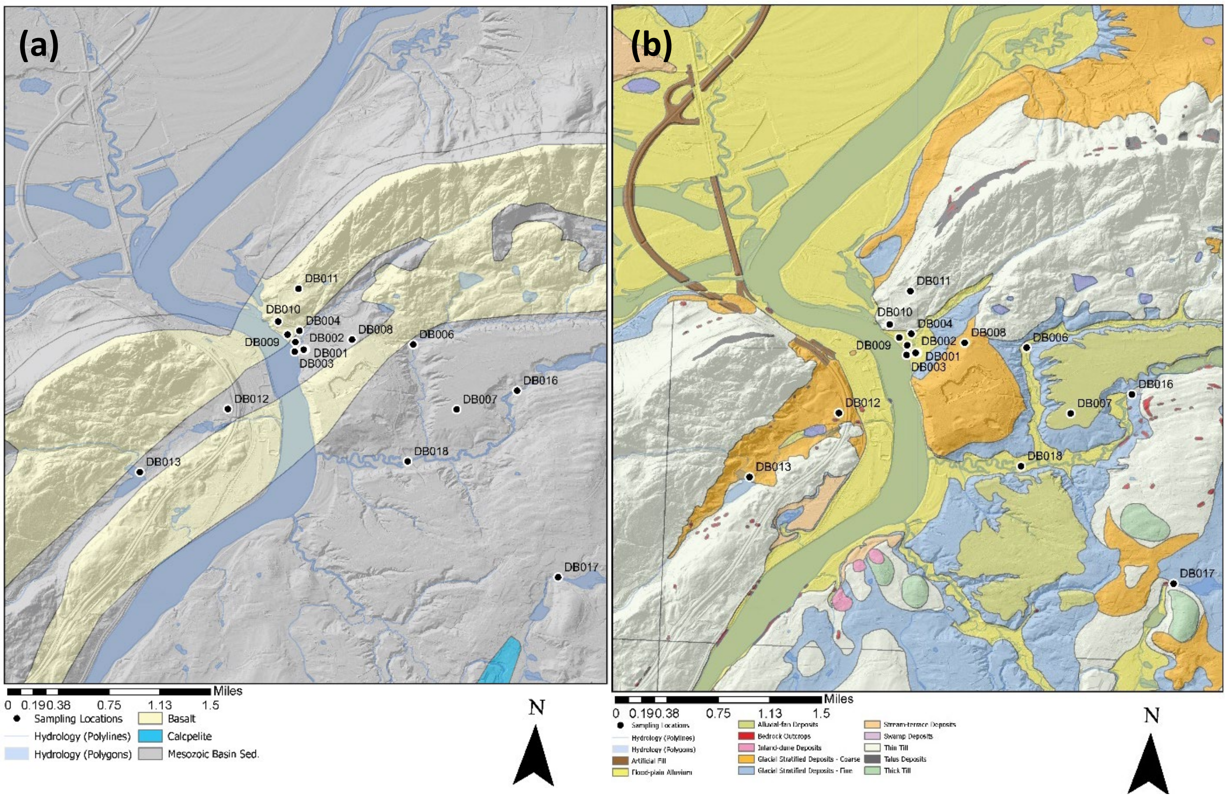


Figure 2. Map of (a) the bedrock, and (b) the surficial geologic setting of the study site.

2.1.2. Hydrogeologic Setting

The South Hadley Dry Brook Hill aquifer is part of the larger connected drainage basin of the Connecticut River which covers roughly 11,320 square miles extending from Northern New Hampshire into Long Island Sound. The watershed area that lies within Massachusetts proper covers about 2,710 miles. The surface and ground-water hydrology of the study area is dominated by topography, underlying geologic materials, and the Connecticut River. The area receives approximately 42 inches of precipitation annually spread evenly throughout the year with precipitation being the primary source of all water in the study area. The sandy soils on the higher elevations of Dry Brook Hill constitute an important area of local recharge. The Dry Brook supply well is completed in the sand and gravel aquifer that underlies the lacustrine sediments near the mouth of Dry Brook. This sand and gravel aquifer is physically contiguous with coarse sediments in Dry Brook Hill. Water in the study area (not pumped from wells) will generally flow to the Connecticut River under natural conditions.

2.2. Purpose

The town of South Hadley has tasked the University of Massachusetts Amherst Hydrogeology research group to construct and run a study to refine the contributing area of the Dry Brook aquifer. This is critical for making informed decisions regarding the sustainability and vulnerability of the Fire District 2 drinking water supply for the town of South Hadley. The group seeks to answer the following essential questions:

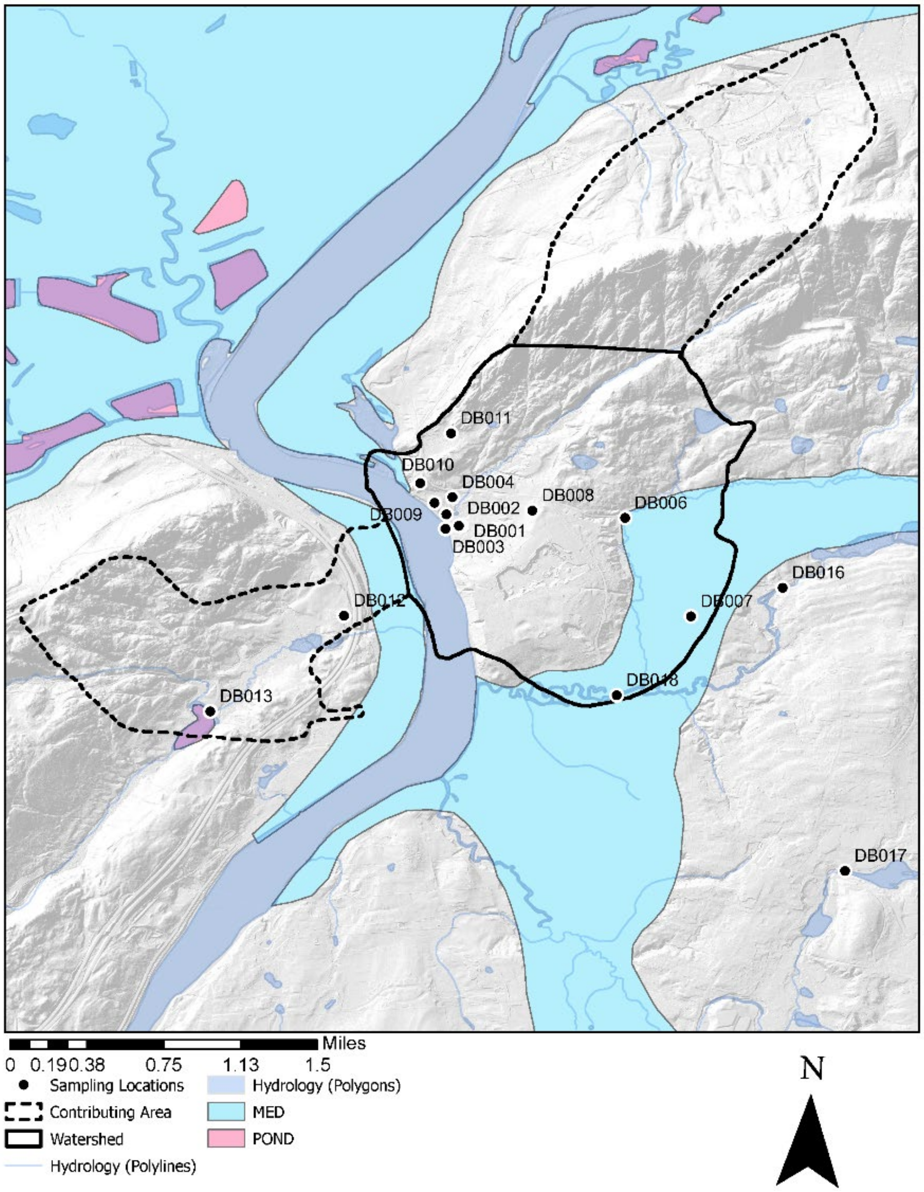


Figure 3. The watershed and larger contributing area to the Dry Brook public supply well indicated by the USGS report (Garabedian and Stone, 2004). Major aquifer delineations are shown as a blue polygon.

1. Has the chemistry of the Dry Brook aquifer changed from the start to the end of the pumping test? If so, how?
2. How different are the Dry Brook pumping wells from other groundwaters?
3. How different is the surface water from the groundwater?
4. How variable is the dry brook well over time?
5. Does the geochemistry of the pumped water support a connection to the Connecticut River?
6. What fraction of produced water is local recharge (i.e., Dry Brook Hill) vs. Induced infiltration from the Connecticut River?
7. What can be concluded from this data regarding the size and residence time of water in the aquifer system?

3. Methods

3.1. Approach

As water moves through the terrestrial hydrologic cycle it transports with it dissolved inorganic and organic solutes, gases, and other complexes. These species give insight into the natural and anthropogenic processes that control hydrologic cycles and connections – i.e. surface water-groundwater. These constituents of water allow us to "trace" how water moves through a hydrologic system and each provides valuable information on key processes controlling these interactions. This environmental tracer study utilizes specific tracers that give insight into residence time and transit time of groundwater, surface-ground water interactions, and hydraulic connectivity between the pumping wells and nearby surface water bodies. The hydrogeochemical tracers we utilize in the is this study are stable Oxygen and Hydrogen isotopes (^{18}O, ^{2}H), the radiogenic isotope of Hydrogen, Tritium (^{3}H), dissolved noble gases in water, Radon gas in water, the concentration of dissolved ions and the anthropogenically produced short-term age tracers Chlorofluorocarbons (CFCs), and Sulfur hexafluoride (SF_6). The approach we take here is to combine each of these tracers, recognizing their various strengths and weaknesses, into a uniform framework that addresses each of the science questions we laid out above.

Stable water isotopes are highly effective tracers of water sources to a given aquifer or water body. By comparing a sampled $\delta^{18}O$ and $\delta^{2}H$ signature relative to atmospheric input signatures and other water bodies, relative connections, and sources of water can be distinguished (Kendall & Coplan, 2001). These isotopes are highly effective and widely used as tracers because the process controlling their fractionation is well understood and as a part of the water molecule itself, the signatures that are imprinted during recharge are maintained through the water cycle, providing essentially a "fingerprinting" of water bodies (McGuire & McDonnell, 2004). Radioisotope signatures in water (^{3}H) offer unique advantages as an age tracer of water. Since they are also part of the water molecule they are conservative so a particular water body will follow a predictable decay (half-life of 12.32 years) during transit from its recharge to the sample point (Lindsey et al., 2019). By constraining the known amphoteric input activity, we can gain valuable insights into the transit of water and potential mixing between waters of different ages. CFCs and SF_6 are gases that were produced by industry starting in the 1950s and their signature in the atmosphere was incorporated into precipitation and therefore recharge. Using this signal in the atmosphere we can model the predicted age of a water sample given its concentration of these gases (Plummer & Busenberg, 2003). The soluble and inert noble gases that are dissolved in rainfall and recharged into the groundwater (He, Ne, Ar, Kr, and Xe) and a suite of their radioisotopes together offer unique insights into connections among water bodies and between them and the atmosphere (Cartwright et al., 2017). The noble gas radon-222 (^{222}Rn) is another often used tracer to study surface water-groundwater interactions. With a half-life of 3.8 days, ^{222}Rn can be used to assess apparent travel times of up to ~15 days of infiltrating river water to groundwater (Gleeson et al., 2018).

3.2. Water Sampling

The group used a tier system of sampling based on how valuable a sample would be to answer the questions of the study and to limit the costs of analysis. There are five tiers of samples with “Tier 1” being the most expansive analysis method. Not every type of analysis was completed for each sample. The “Tier” indicates what samples were collected for a particular location. In total 63 samples were taken for the suite of analyses described above. Samples were taken according to the analysis method with varying sizes of sample bottles and colored label tape. Copper tubing was used for specialized dissolved gas collection.

Table 1. Summary of sampling procedure.

Tier 1		**Tier 2**		**Tier 3**		**Tier 4**		**Tier 5**	
Sample	Supplies	Sample	Supplies	Sample	Supplies	Sample	Supplies	Sample	Supplies
Field Parameters	YSI	Field Parameters	YSI	Field Parameters	YSI	Field Parameters	YSI	Field Parameters	YSI
Dissolved Noble Gases	2 clamps, copper tube, tubing	Radon	2L plastic bottle	Radon	2L plastic bottle	Radon	2L plastic bottle	H+O - Stable Isotopes	15mL bottle
Radon	2L plastic bottle	CFCs	125mL brown glass	3H - Tritium	1L bottle	H+O - Stable Isotopes	15mL bottle		
CFCs	125mL brown glass	SF6	1L safety coated glass bottle	H+O - Stable Isotopes	15mL bottle	Major and Minor Elements	2 30mL bottles		
SF6	1L safety coated glass bottle	3H - Tritium	1L bottle	Major and Minor Elements	2 30mL bottles	Alkalinity	Alkalinity test kit		
3H - Tritium	1L bottle	H+O - Stable Isotopes	15mL bottle	Alkalinity	Alkalinity test kit				
H+O - Stable Isotopes	15mL bottle	Major and Minor Elements	2 30mL bottles						
Major and Minor Elements	2 30mL bottles	Alkalinity	Alkalinity test kit						
Alkalinity	Alkalinity test kit								

The sample sites include a variety of surface water bodies, residential wells, observation & monitoring wells, as well as the Dry Brook production wells. To better understand the system and to answer the questions of the study, sampling locations were chosen to be representative of the watershed area and boundaries that influence both the production wells and the surrounding surface waters. To simulate changes to the sources of water within the Dry Brook aquifer, supplying the Dry Brook production well, a set of samples was taken before during, and after a continuous pumping test was conducted. The pump test was run ~1000-1200 GPM for 12 hours. In total, 15 sampling sites were used for this study.

4. Geochemical Results

4.1. Tritium

We collected 8 water samples from wells and surface waters in the Dry Brook well field area and analyzed their Tritium (^{3}H) activity values (Table 2). The ^{3}H activity in the atmosphere has recently reached its stable natural production level as the “bomb peak” has fully decayed to background levels (Lindsay et al., 2019). A continuous record of measured ^{3}H activity in precipitation has been recorded in Boston, MA for several decades. The average monthly background value at this station since the bomb peak signal was no longer recognizable (2005-2022) is 7.9 ±1.6 TU (Michel et al., 2018). The ratio between this value and the sample value provides a measure of the connection that exists between each sample and the precipitation input that occurred over that recent period.

Since it was not possible to sample multiple times along known groundwater flow paths for this study and our goal was to specifically investigate the interactions between the surface and deep aquifers, we apply a simple but effective method to analyze these tritium values (Moran et al., 2024). This fraction (or percent of recent precipitation) provides a reliable estimate of the relative age of the sampled waters and the water bodies they represent. For example, a sample with a 100% young fraction value indicates that water is sourced entirely from precipitation after ~2005, this would be a very young water signature. A sample closer to 30% indicates approximately 30% of that water body is sourced from water recharged after ~2005, the rest is older water recharged entirely before 2005. It is important to also point out that because ^{3}H is a highly conservative tracer the signal incorporated into rainfall is well mixed in the atmosphere, therefore, the ^{3}H input signal is quite stable over time. This is a useful way to identify the strength of the connection between the atmosphere and a given water body.

Results from our sampling campaign indicate as we would expect, a strong distinction in the strength of the connection between the surface waters and the aquifers (Table 2). The Connecticut River shows it's entirely composed of young water indicating a very short average (weeks to months) residence times of that water. This means that water infiltrating into the aquifers from the river would essentially show the same tritium signature that recent rainfall would show. The other two streams in the area, Dry Brook and Elmer Brook are also composed primarily of young water although it appears that somewhere between 5-15% of that water is composed of older baseflow inputs from the upgradient aquifers. The five groundwater samples show very different signatures than these surface waters with a young water content of between 34%-45%. OBS well 7-97 has the highest value, perhaps related to its proximity to the CT river and near the hypothetical flow path along which CT river water would flow toward the Dry Brook production well (Figure 4).

The three samples taken from Dry Brook #2 Production well are from 1) before the test during static conditions, 2) during pumping taken ~2 hours after pumping began, and 3) at the end of the test. This sample set provides valuable insight into the source of water to that aquifer under static conditions and the source of water during pumping. Under static conditions the production well aquifer at depth is composed of approximately 1/3 young water, the rest is older water flowing from the eastern (and perhaps western) upgradient aquifers along long transit time (years to decades) flow paths. The percentage of young water fraction increases over the set of three samples by a total of 8%. The results indicate that the water extracted from the well becomes progressively younger over time. This may be due to mixing with the aquifer water similar to OBS well 7-97 closer to the Connecticuit River but a rapid change like this over only a few hours of pumping likely indicates that there is also likely mixing with water coming directly from the Connecticuit River to explain the signature we observe.

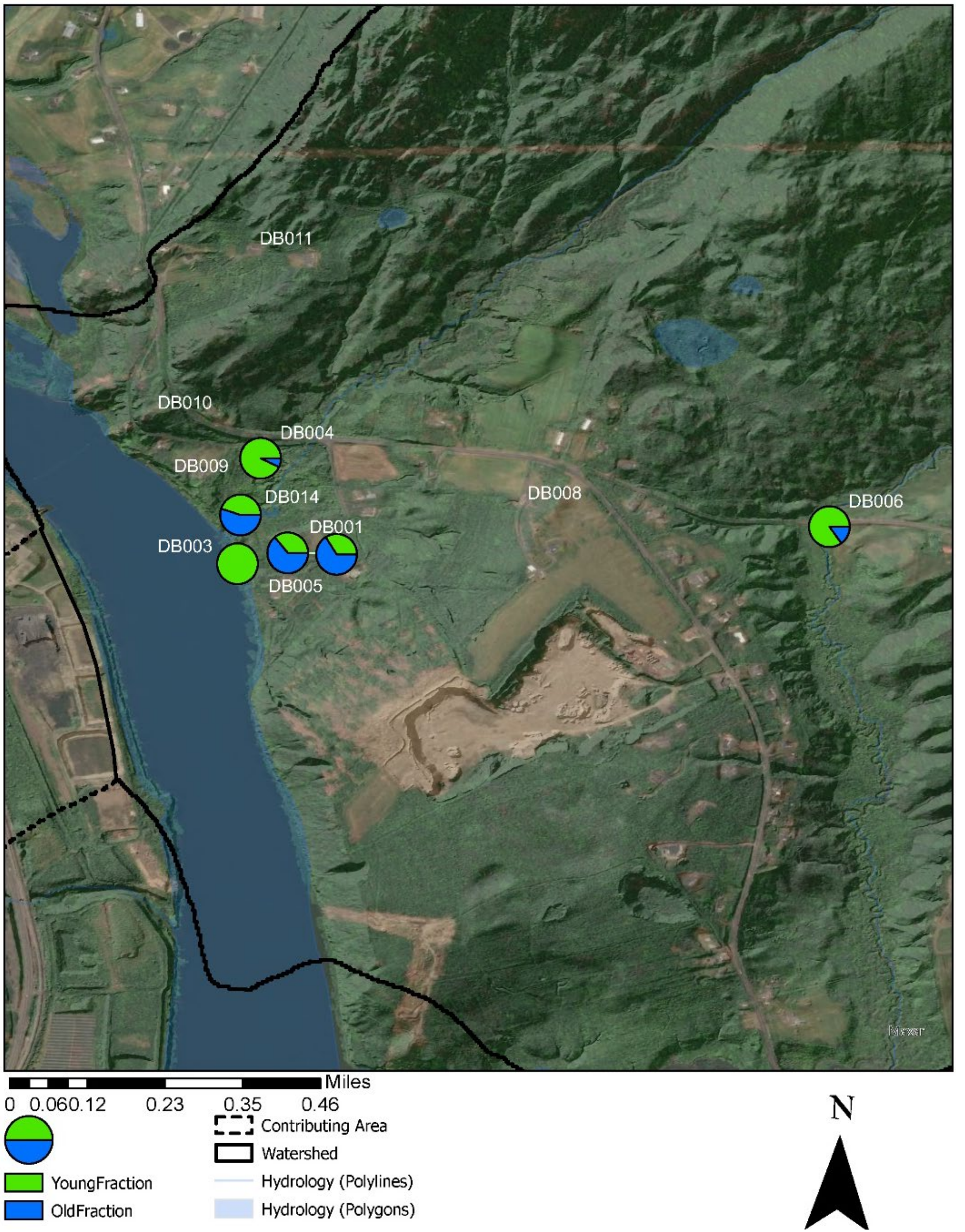


Figure 4. Map of ^{3}H sample results shown as the young vs. old water fraction.

Table 2. Summary of measured ^{3}H activity in water.

Sample ID	Name	Sample Date	Analysis Date	^{3}H Concentration (TU)	1 Sigma Analytical Error	^{3}H Sample/^{3}H Background - Young Fraction (%)
	Boston, MA ^{3}H in Precipitation Background	2005-2022		7.90	-	-
DB006	Elmer Brook @ Pearl St.	7/31/2023	12/22/2023	6.71	0.28	85%
DB004	Dry Brook Stream	7/31/2023	12/22/2023	7.36	0.30	93%
DB003	CT River, neighbor's dock	7/31/2023	12/22/2023	8.70	0.38	110%
DB001	Dry Brook Well #2 - Before test	7/28/2023 - 10:40 am	12/27/2023	2.70	0.12	34%
DB001	Dry Brook Well #2 - Start of test	7/31/2023 - 6:55 am	12/22/2023	3.01	0.16	38%
DB001	Dry Brook Well #2 - End of test	7/31/2023 - 6:14 pm	12/14/2023	3.28	0.23	42%
DB005	OBS Well 6-97	7/31/2023	12/8/2023	2.87	0.16	36%
DB014	OBS Well 7-97	7/31/2023	12/22/2023	3.52	0.63	45%

4.2. SF6 and CFC

We utilized the human-derived pulses of CFCs and SF6 gases that were put into the atmosphere, dissolved in precipitation, and then moved through the hydrological system. The nature of this signal across multiple types of these gases allows for a determination of the direct ages of the sampled water. The models used to determine the water age from atmospheric concentration input functions were developed in the 1990s (Epler, 1990; Busenberg and Plummer, 1991, 1992, 1997).

A total of 8 water samples were collected for CFCs and SF6 alongside the same 8 sample analyses for ^{3}H described above to build in some redundancy of age-tracing results using very different techniques. The results of the age models are summarized in Table 4. Reflecting the ^{3}H results from Dry Brook Well #2, the water age from static conditions before pumping to after pumping was complete became progressively younger. Specifically, the average estimated water age decreased from between 46-27 years old to between 39-16 years old with Sf_6 showing younger ages than CFCs. They both show a clear signal of a younger source of water being drawn into the aquifer when it is pumped. Additionally, the aquifer near OBS well 7-97 closer to the Connecticut River contains substantially younger water than OBS well 6-97 farther from the river.

Table 3. Summary of SF6 and CFCs measured concentrations in water.

SF6

Sample ID	Name	Sample Date	SF6 Conc. - Raw (fMol/L)	SF6 Conc. in Water - HS Corrected (fMol/L)	Piston Flow Model SF6 Rech. Year	Piston Flow Model SF6 Rech. Age, Years
DB001	Dry Brook Well #2 - Before test	7/28/2023 - 10:40 am	1.34	1.37	1997	26.6
DB001	Dry Brook Well #2 - Start of test	7/31/2023 - 6:55 am	1.44	1.48	1998.5	25.1
DB001	Dry Brook Well #2 - End of test	7/31/2023 - 6:14 pm	2.19	2.25	2007.5	16.1
DB005	OBS Well 6-97	7/31/2023	1.20	1.23	1995	28.6
DB014	OBS Well 7-97	7/31/2023	2.71	2.78	2013	10.6

CFC

Sample ID	Name	Sample Date	CFC-11 (pmoles/kg)	CFC-12 (pmoles/kg)	CFC-113 (pmoles/kg)	CFC-11 Rech. year	CFC-12 Rech. year	CFC-113 Rech. year
DB001	Dry Brook Well #2 - Before test	7/28/2023 - 10:40 am	7.02	2.94	0.21	1981.5	1980.5	1977.5
DB001	Dry Brook Well #2 - Start of test	7/31/2023 - 6:55 am	6.84	3.16	0.21	1981	1981.5	1977.5
DB001	Dry Brook Well #2 - End of test	7/31/2023 - 6:14 pm	6.80	2.83	0.22	Post 2001	Post 2001	1984

4.3. Stable Water Isotopes

A total of 114 water samples were collected at 18 surface water and groundwater sites for analysis of stable oxygen and hydrogen isotope signatures. Results indicate unique signatures of surface water and the Dry Brook aquifer (figure 5). The local surface waters and Connecticut River water cover a much larger range of variation and appear to follow a slightly different meteoric water line than the groundwaters (e.g. shifted to the right in the plot) showing its source is more closely tied to shorter-term inputs than the groundwater and are influenced by evaporative effects (Figure 5b). The groundwater samples cluster over a smaller range reflecting the fact that its source is primarily from longer residence time groundwater storage with a more muted response to precipitation events and short-term climate changes. The substantial overlap in $\delta^{18}O$ signatures between the groundwater and a majority of the Connecticut River samples, particularly since much of the Connecticut River watershed has a colder, high-elevation climate than the study site, indicates the likelihood of some direct interconnection between the Connecticut River and the Dry Brook aquifer.

Observing the isotopic signature in the Dry Brook wells and Connecticut River water over time offers some additional clues about these atmosphere-surface water-groundwater connections. The δ^{18}O signature in the Dry Brook wells is quite consistent over the year, ranging between -8.0 and -8.7 during the warmer months and -8.4 To -8.6 during the colder months, likely reflecting the influence of some more enriched water entering the aquifer during warmer months (Figure 6a). In addition, the larger range in the summer may indicate more inputs from the surface water bodies to the aquifer during the warmer months. Looking at the Connecticut River water during July we can see that even in the summer, its δ^{18}O signature is very close to -8.5 except for two excursions where the signature becomes much less negative, likely the result of local large rain events (Figure 6b). The fact that we see rapid and significant changes towards a less negative signature in the Dry Brook Aquifer waters during the warm months indicates this may be a signal of surface water entering the deep aquifers.

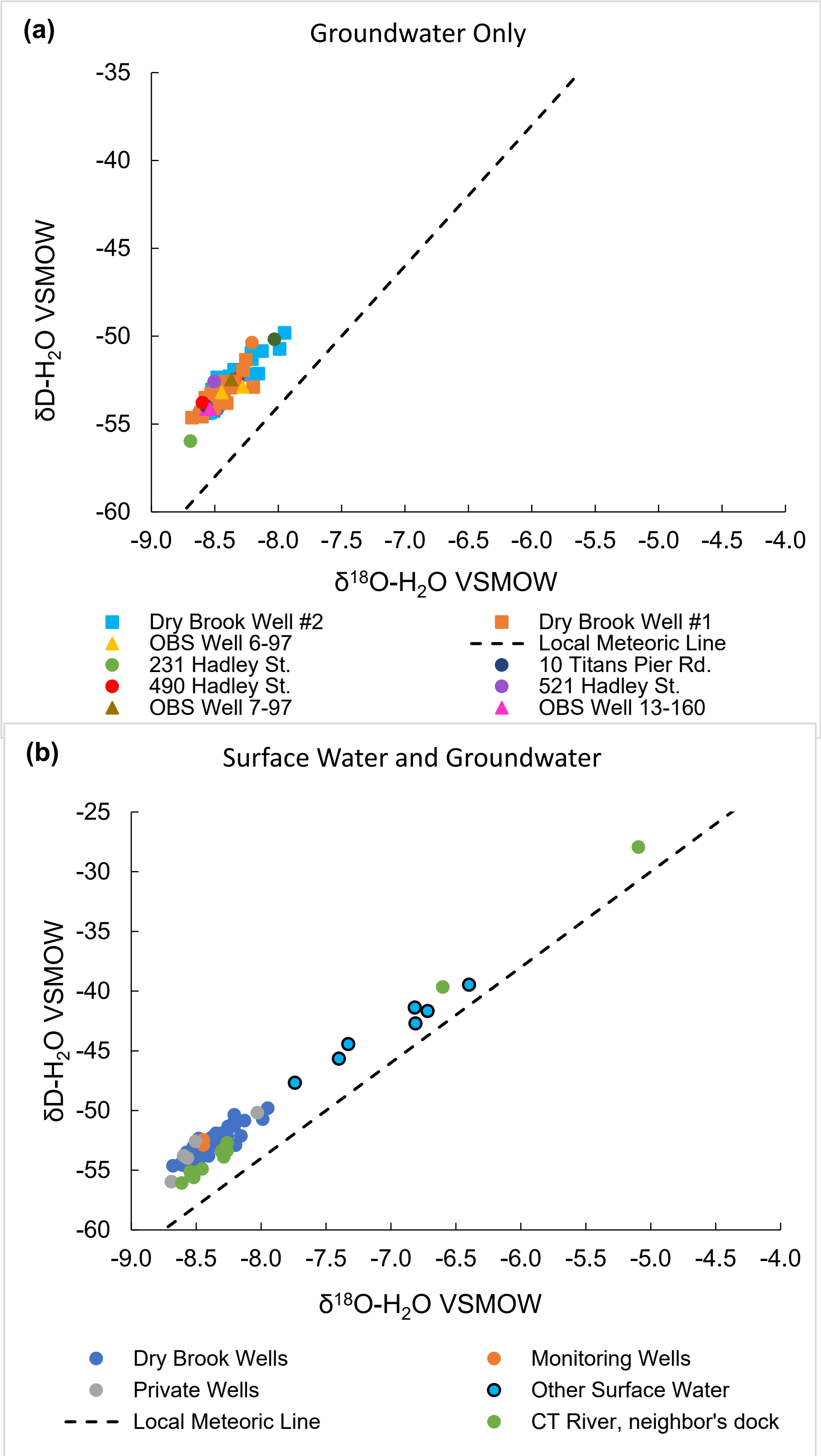


Figure 5. Results of stable water isotope data from surface waters and groundwaters plotted in $\delta^{18}O$-H_2O VSMOW vs δD-H_2O VSMOW space against the Local Meteoric Water Line for the region (Cole and Boutt, 2021).

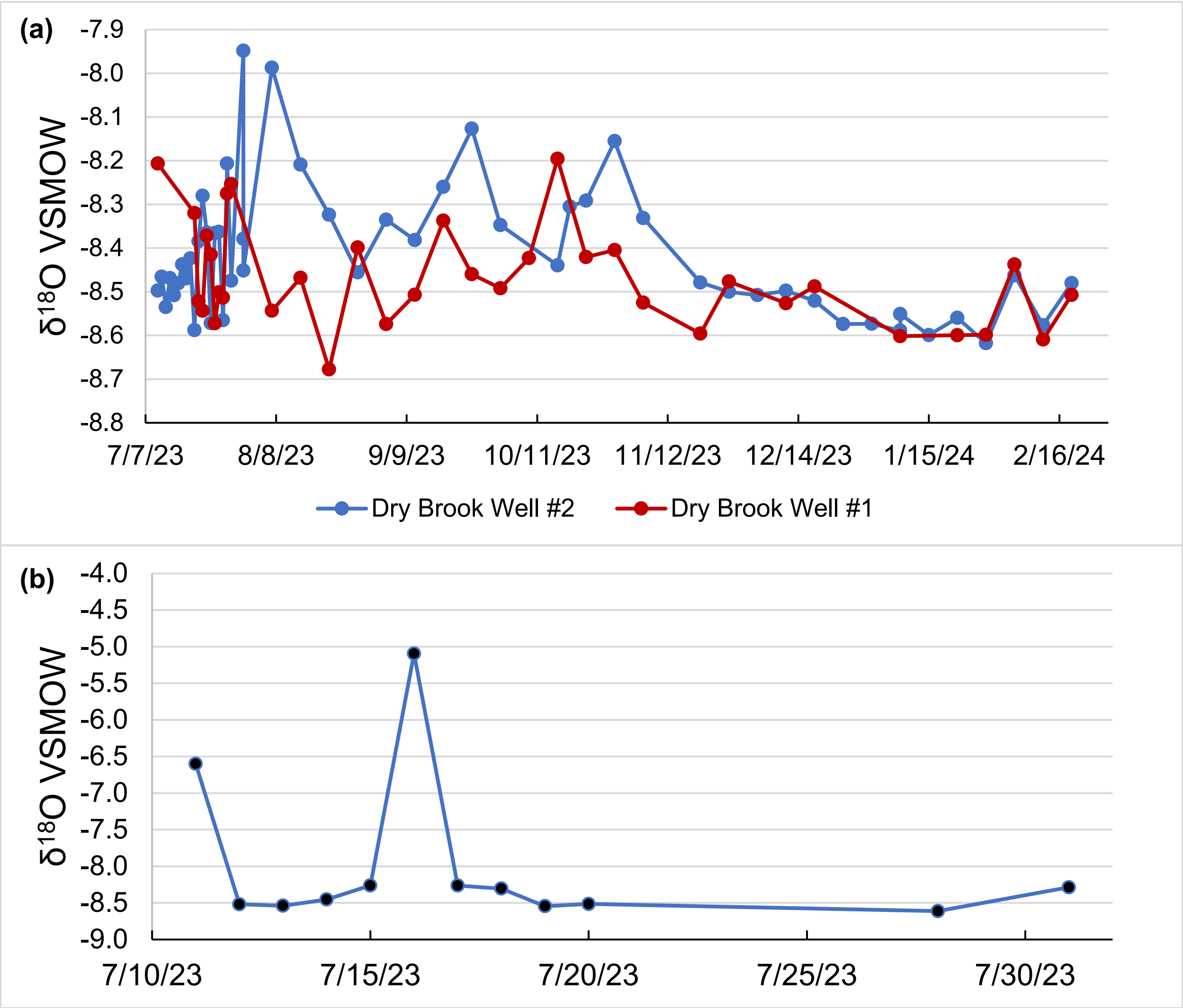


Figure 6. Time series of $\delta^{18}O$ data collected from (a) Dry Brook Well #1 and #2 throughout the project and, (b) from Connecticut River through the month of July 2023.

4.4. Major and Minor Elements

The concentration of dissolved elements in the sampled water bodies reflects the hydrogeological conditions of the flow paths contributing to them and offers insights into distinctions between them and mixing occurring both under long-term average conditions and on shorter time scales. Plotting the ionic compositions of the waters together in Piper plot space shows that the Dry Brook Well aquifer waters are Calcium-Sulfate-dominated, whereas the surface waters are lower in Calcium and higher in Sodium and Potassium (Figure 7). The other groundwaters largely occupy a range covering these two types with a few outliers likely reflecting local hydrological conditions in those locations. As Dry Brook Well #2 was pumped, the hydrogeochemical composition slowly moved towards Dry Brook Well #1, becoming slightly more Sodium and Chloride rich and losing some Calcium, a water type slightly more reflective of the Connecticut River water (DB003) and less reflective of the Dry Brook Stream water

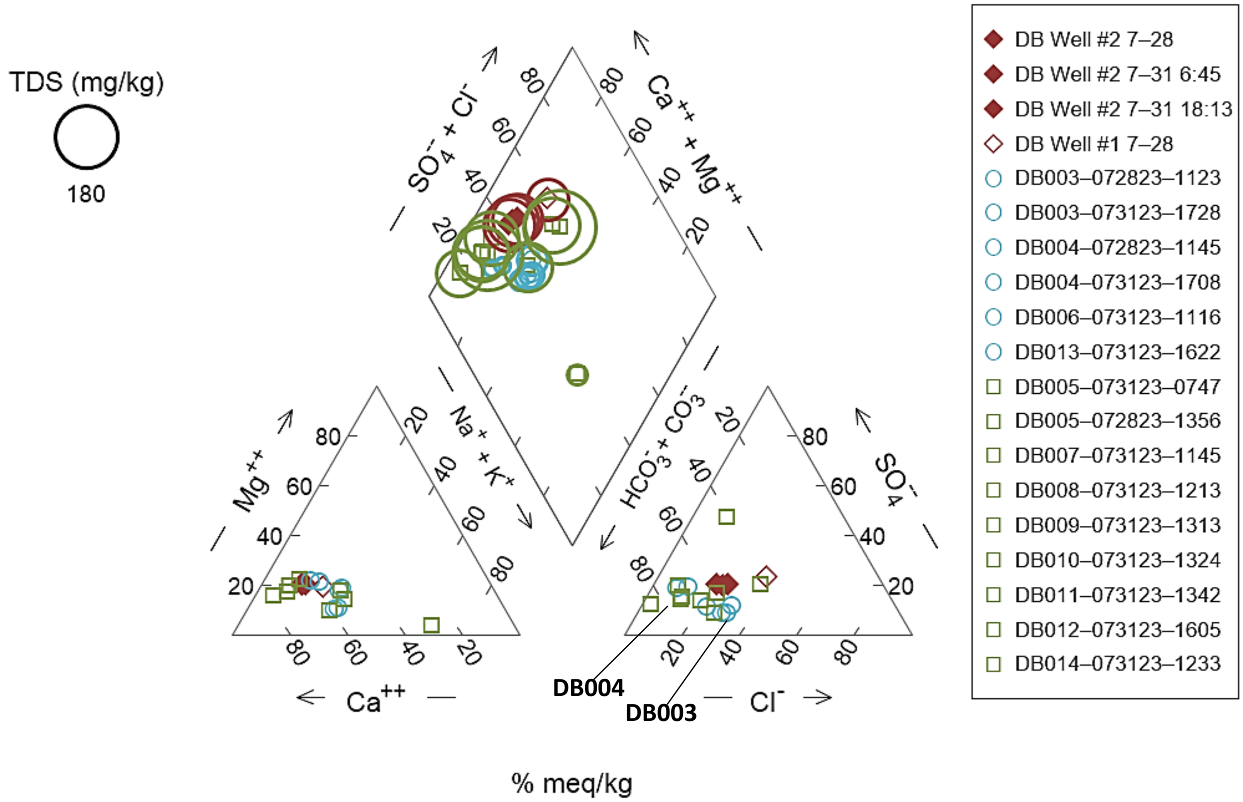


Figure 7. Piper plot of the major dissolved ions measured in the dry brook well groundwaters (Red diamonds), other groundwater (green squares), and surface waters (blue circles). Key end-member surface water sites, DB004 (Dry Brook Stream) and DB003 (Connecticut River) are indicated

(DB004). This rather slight but observable shift given the short pumping test duration may reflect more water mixing into the aquifer from a source that looks like the Connecticut River water and less from a source that looks like the local surface water.

4.5. Radon

Radon is a useful way to identify differences between ground and surface waters. As this analysis was done in-house rather than through a lab, it has been included here with other samples processed at UMass. Since Earth's atmosphere has virtually no source of Radon (^{222}Rn), water in equilibrium with the atmosphere is practically devoid of Radon (Popp et al., 2021). As Radon exists as a dissolved gas, we can understand that through normal evaporative processes it would naturally be lower in surface water bodies because of exposure to air and the opposite would hold true for groundwater. Radon measurements were taken with two-liter soda bottles

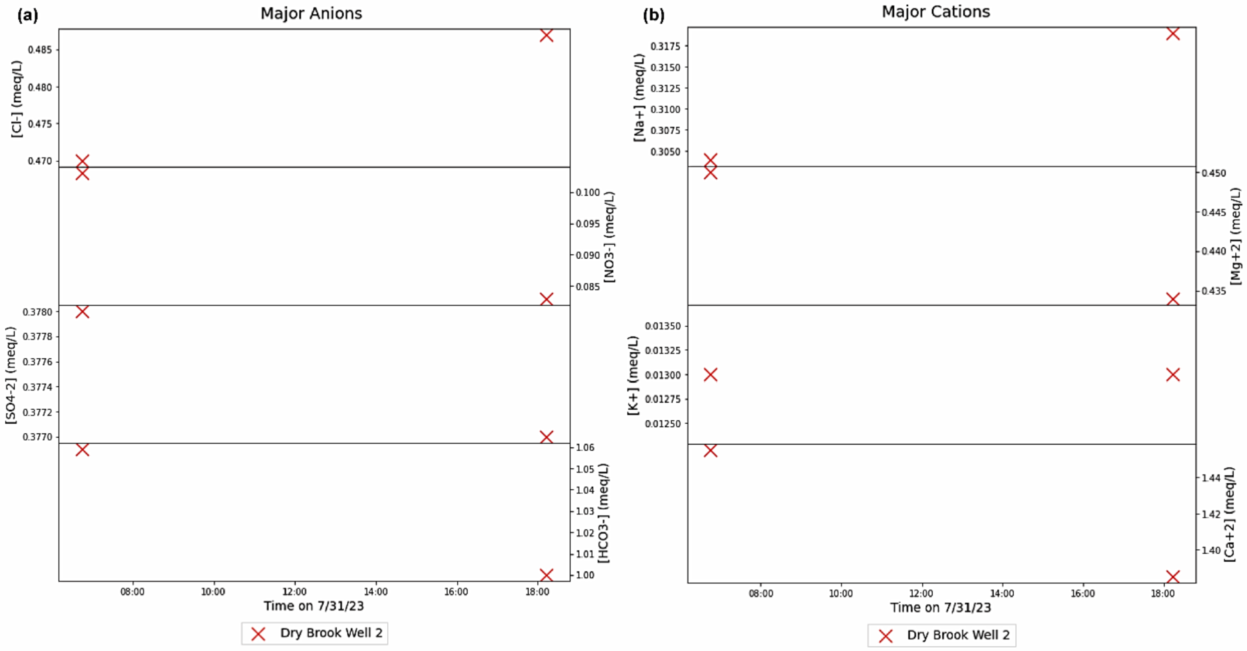


Figure 8. Time series of major Anions (a) and Cations (b) in the water pumped from the Dry Drook well at the beginning of the pump test and at the end of the pump test.

and processed using Durridge's RAD7 Big Bottle System® in our temperature-controlled lab at the University. Results were corrected for relative humidity and exported using Durridge's Capture® software.

The results of our analysis of Radon activity at 14 sites and a total of 19 individual water samples are summarized in Table 5. A few key observations can be made from the data. First, the Connecticut river waters have the lowest activities, reflecting water largely in equilibrium with the atmosphere. Second, the activity of ^{222}Rn in Dry Brook Well #2 rose substantially from before the test to the end of the test. Third, relative to other groundwater samples, Dry Brook Well #2 appears to be near average. Also, the pre-pumping Radon activity in Dry Brook Well #2 was lower than in Well #1, rising to match it at the of the pumping test. Since the changes observed during pumping are relatively small, especially compared to the differences between the groundwater samples and the surface water samples, this may indicate that the water entering the well towards the end of pumping is a mixture of the higher activity groundwater similar to DB008 (a bedrock aquifer well to the east) and some surface waters of much lower activity, similar to DB003 (Connecticut River water). Given the positive shift, this indicates a small portion of the surface water is entering the aquifer. Another interesting result is that the groundwater in well DB014, just to the northwest of Dry Brook Well #2 is elevated in ^{222}Rn which may indicate a more direct connection to the Connecticut River in that portion of the aquifer, consistent with the ^{3}H-derived age results.

Table 4. Summary of Radon-222 activity in water results.

Sample ID	^{222}Rn (PCi/L)	Time Collected	Site Type	Water Type
DB001	308	7/28/23 10:51	Production Well	Ground Water
DB001	413	7/31/23 6:55	Production Well	Ground Water
DB001	488	7/31/23 18:11	Production Well	Ground Water
DB002	488	7/28/23 12:17	Production Well	Ground Water
DB003	6	7/28/23 11:22	Surface Water	Surface Water
DB003	11	7/31/23 17:31	Surface Water	Surface Water
DB004	30	7/28/23 11:46	Surface Water	Surface Water
DB004	43	7/31/23 17:13	Surface Water	Surface Water
DB005	689	7/28/23 14:01	Observation Well	Ground Water
DB005	351	7/31/23 7:45	Observation Well	Ground Water
DB006	16	7/31/23 11:14	Surface Water	Surface Water
DB007	60	7/31/23 11:42	Private Well	Ground Water
DB008	1250	7/31/23 12:08	Private Well	Ground Water
DB009	428	7/31/23 13:12	Private Well	Ground Water
DB010	179	7/31/23 13:29	Private Well	Ground Water
DB011	280	7/31/23 13:47	Private Well	Ground Water
DB012	27	7/31/23 16:09	Private Well	Ground Water
DB013	8	7/31/23 16:23	Surface Water	Surface Water
DB014	497	7/31/23 12:36	Observation Well	Ground Water

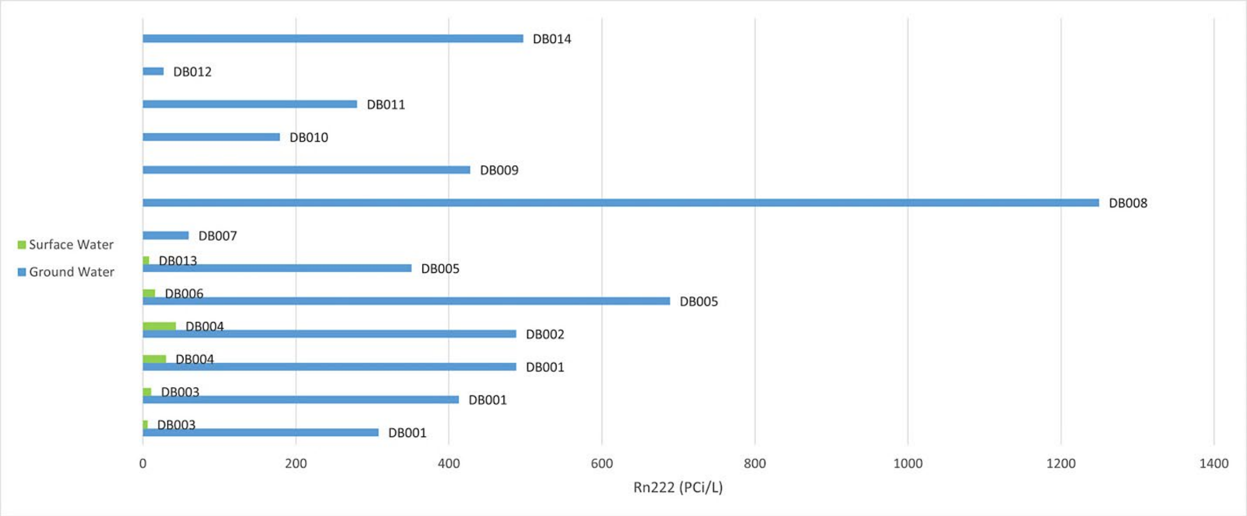


Figure 9. Summary plot of Rn-222 activities from sampled waters

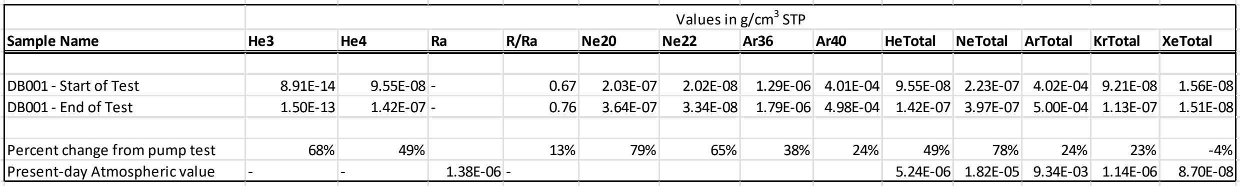
4.6. Dissolved Gases

We collected a suite of noble gases and their isotopes from the Dry Brook Well #2 at the start of pumping and at the end of the test. To look specifically at how their concentrations and activities changed between these two samples, we calculated a simple % change column (table

3). We can see that overall the concentrations of noble gases increase modestly (between -4% and 78%) by the end of the test. Looking at these values relative to the average atmospheric contractions, it appears that the water sampled at the end of the test is less equilibrated to the atmosphere than at the start of the test. Meaning there is no observable signal of surface water mixing in. However, it's important to note that this does not mean there is none, just that any signal it has was outweighed by the signal from less atmospheric-equilibrated groundwater.

Looking at Tritogentic (^{3}He) vs radiogenic Helium (^{4}He) we can see a modest increase in the activity of both by the end of the test the ratio of ^{3}H/^{4}He also increases. Though there are several possible reasons for these changes, similar to the noble gas results discussed above, these data are consistent with an influx of both surface water and groundwater with more radiogenic Helium.

Table 5. Summary of Dissolved Gas results from pump test of Dry Brook well. DB001A was taken at the start of the pump test, and DB001B at the end of the test.



	Values in g/cm^{3} STP												
Sample Name	**He3**	**He4**	**Ra**	**R/Ra**	**Ne20**	**Ne22**	**Ar36**	**Ar40**	**HeTotal**	**NeTotal**	**ArTotal**	**KrTotal**	**XeTotal**
DB001 - Start of Test	8.91E-14	9.55E-08	-	0.67	2.03E-07	2.02E-08	1.29E-06	4.01E-04	9.55E-08	2.23E-07	4.02E-04	9.21E-08	1.56E-08
DB001 - End of Test	1.50E-13	1.42E-07	-	0.76	3.64E-07	3.34E-08	1.79E-06	4.98E-04	1.42E-07	3.97E-07	5.00E-04	1.13E-07	1.51E-08
Percent change from pump test	68%	49%		13%	79%	65%	38%	24%	49%	78%	24%	23%	-4%
Present-day Atmospheric value	-	-	1.38E-06	-					5.24E-06	1.82E-05	9.34E-03	1.14E-06	8.70E-08

4.7. End Member Mixing

End member mixing models using conservative tracers are an effective way to determine the degree of mixing from various sources contributing to a given sample (Clark & Fritz, 1997). Here we utilize the conservative tracers Cl^{-}, ^{3}H, and δ^{18}O to estimate the proportion of water sourced from the Connecticut River and the static (or average composition) aquifer water that composes the sampled water in Dry Brook Well #2 after pumping. Using the equation: $C_{Final} = F_a \times C_a + C_b \times F_b$, where C is the concentration of the tracer in each end-member a and b, and F is the fraction of each end-member in the sample. Using three different tracer results will produce somewhat different estimates of the mixing proportions due to uncertainties inherent in the assumptions of the model. Using the ^{3}H activity we estimate that 9.7% of the water pulled into the well at the end of pumping is from the Connecticut River; using δ^{18}O it is estimated that 19.9% is from the Connecticut River; and using Cl^{-}, the estimate is quite a bit higher at 42.8%. Using the estimates based solely on the isotopic tracers contained within the water molecule itself as the most reliable, conservative tracers we estimate the portion of water entering the aquifer from the Connecticut River during the 12-hour pump test is approximately 20%. The other sources of water are likely from the surrounding bedrock and deep alluvial aquifers.

5. Conclusions

Based on the results presented above we specifically address each of the following science questions that were posed:

1. Has the chemistry of Dry Brook changed from the start to the end of the pumping test? If so, how?

Yes, the hydrogeochemistry of the water did change from the start of the test to the end. In section 3.4 we describe these results in detail. Overall the changes are minor and indicate that the water in the aquifer is fairly uniform with respect to its chemical composition, at least through a 12-hour pumping test.

2. How different are the Dry Brook pumping wells from other groundwaters?

Both hydrogeochemically and isotopically the Dry Brook pumping wells are distinct from the other groundwaters sampled, the exception being OBS well 7-97 which shows evidence that it lies within a groundwater flow path and connection between the Connecticut River and the Dry Brook Well #2. The other groundwaters are slightly more depleted in $\delta^{18}O$ overall than the Dry Brook wells and also have a hydrogeochemical profile more similar to the surface waters than the Dry Brook well waters.

3. How different is the surface water from the groundwater?

In their bulk composition, the surface waters are very distinct from the groundwaters in the study area, as would be expected in a hydrogeological setting such as this with a partially confined aquifer >100 ft below the surface. Both the hydrogeochemical characteristics and isotopic signatures are distinct between the surface and groundwater. This proved to be an advantage in this study because it allowed for two distinct end-members to be defined and to effectively apply the suite of tracers to address the questions we laid out.

4. How variable is the dry brook well over time?

As we describe in Section 3.3, using consistent stable isotope data collected for this study we can see that the Dry Brook well aquifer water shows some variability over time. Nearly all of the variability occurs in the warm months with its $\delta^{18}O$ signature ranging by ~0.7 ‰ with rapid changes over weekly time scales while also maintaining a relatively consistent baseline signature through the year. This is indicative of an aquifer with some connection to the surface water hydrology of the area (namely the Connecticut River), but also one that is receiving the majority of its water volume from longer flow path groundwater storage in the aquifer. This conclusion, reached through a purely hydrochemical tracer analysis, supports the findings of the physical hydrological assessment described in the USGS Study of the Dry Brook Public-Supply Well.

5. Does the geochemistry of the pumped water support a connection to the Connecticut River?

Yes, as described in the above sections, there is evidence from various tracers that there is a possible connection between the pumped water and the Connecticut River. These connections likely operate on seasonal to multi-annual flow paths as the river water transits through sediments and is naturally filtered.

6. What fraction of produced water is local recharge (i.e., Dry Brook Hill) vs. Induced infiltration from the Connecticut River?

Based on the results of the two-end member mixing model described in Section 3.7, the fraction of Connecticut River water in the produced water at Dry Brook Well #2 is between 10% and 42% with the most likely value being about 20%. That is, approximately 20% of the water pumped from the well is induced infiltration from the Connecticut River and 80% is from groundwater storage sourced from local recharge. This value specifically reflects the conditions in the month of July but we believe it represents the hydrogeological characteristics of this site and therefore it is unlikely to vary much over the year. The main caveat we would add here is that this may represent a slightly low-end value as the test conducted to sample the produced water was only 12 hours long whereas, during regular water supply operations with more sustained pumping, more infiltration could be expected to be induced. It's important to consider that this water isn't directly coming from the river but infiltrated through 50-100 feet of sediment.

6. Next Steps

We believe we addressed the questions we sought to answer in this study and our findings provide valuable information for water managers in the Dry Brook Aquifer. However, a few key limitations created uncertainty in the results and required assumptions to be made about the hydrogeological representativeness of the samples collected. Only one full set of samples could be collected representing one snapshot of the system at that time. The time series data of stable water isotope signatures was invaluable but if we were able to pair that time series to multiple snapshots of the whole system, we could reduce uncertainty substantially. We would recommend sampling a set of key sites during each season along with weekly stable water isotope sampling of the supply well (during pumping) and the Connecticut River water. A long-term pumping test (multi-day) would also provide invaluable information to support our conclusions about the mixture of sources of water to the supply well and in the aquifer. Other tools to further reduce uncertainty would be geophysical surveys (TEM, AEM, NMR, etc.) to better map out the aquifer and the installation of a multipiezometer well nest with piezometers screened in the bedrock, deep alluvium, and shallow alluvium.

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